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Electron beam welding transmission components

by FJ Becket* p.551-554

The application of electron beam welding (EBW) to the fabrication of transmission parts such as gear clusters, splines, couplings and clutches represents the most significant growth area experienced by the process since its original exploitation by aero-engine designers during the 1960s. In this article the electron beam welding process is described and its potential advantages and limitations are discussed. Particular mention is made of the suitability of the commonly used grades of direct hardening and case hardening steels to a welded method of manufacture, with recommendations on their selection.

Gearing and power transmission systems are used in products as diverse as measuring instruments, machine tools, cars, trucks and tractors, aero and marine engines, pumps and power generation equipment. Indeed, practically any device with moving parts includes some form of transmission system.

A welded fabrication is an attractive solution for the design and manufacture of such components providing that it satisfies certain criteria, such as achieving good joint strength, causing negligible distortion and not adversely affecting load bearing surfaces of the component. Electron beam welding meets these requirements and also allows a number of 'design opportunities' to be exploited. These are outlined below.

☐ *Compactness.* The physical size of a component, eg, a gear cluster, is often determined by the spacing needed by the hobbing cutter to clear the larger of the two gears. By manufacturing the gears separately this problem is avoided and the gears can be assembled close together, figs 1 and 2. In reducing the size of individual components the whole gear box can be made more compact, lighter in weight and can probably be produced more economically.

☐ *Machining economics.* Creating two or more simple shapes can be cheaper than making a single complex component. This is certainly true of gear clusters of different diameters which, if made separately, can be assembled on mandrels for hobbing in batches rather than individually. Quite complex gear designs become viable by adopting a welding fabrication route, giving scope for an innovative approach to product design.

☐ *Manufacture from stock materials.* Gears, shafts and splines, etc, can be made from readily available stock sizes of bar and tube sections, avoiding the need for forgings or castings. This is an important consideration at the prototype or development stage and is equally important when only limited production runs are expected. For high production components both forged and cast parts are used to advantage in welded fabrications.

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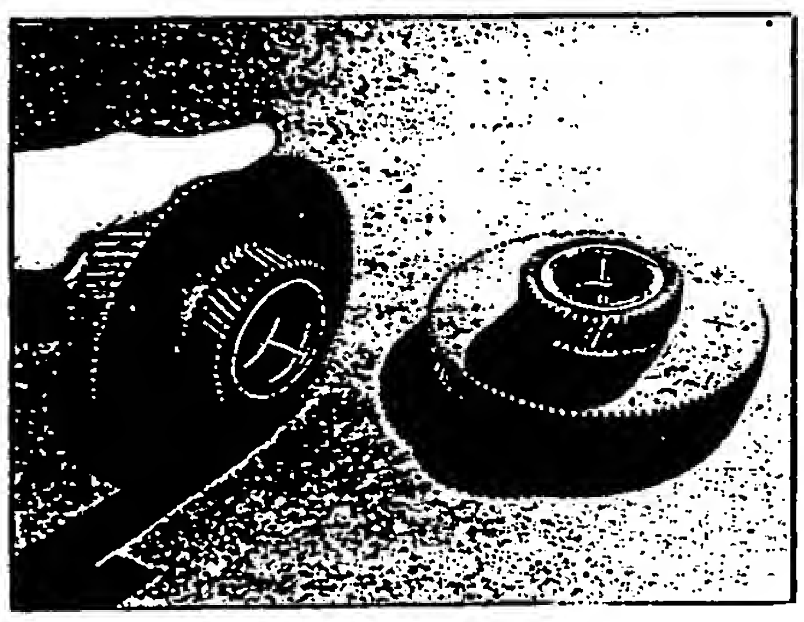
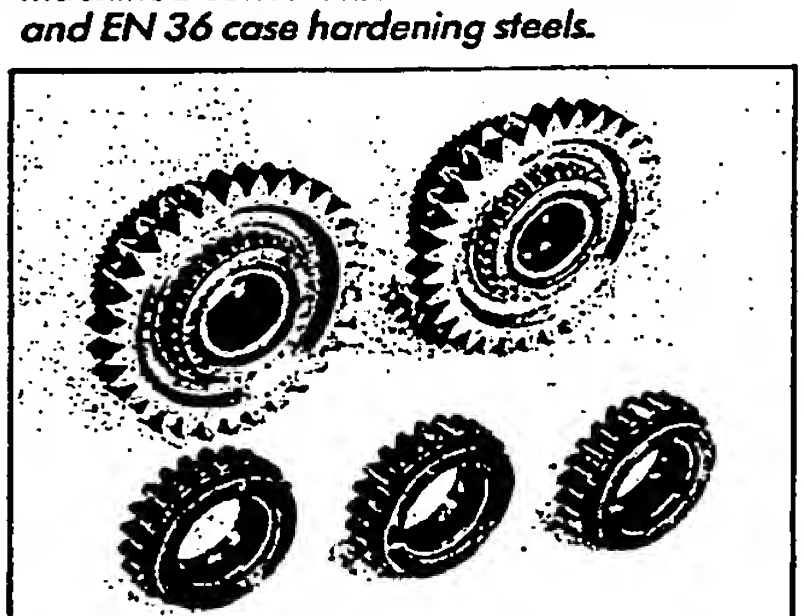


Fig 1. Gear cluster illustrating the compactness of an EB welded fabrication.

☐ *Dissimilar materials.* Many differing material specifications can be EB welded, eg, alloy and stainless steels to nickel and copper base alloys; copper base alloys to nickel alloys; and SG iron to copper base alloys. In gear design it is common practice to shrink fit a phosphor-bronze rim onto a case hardened steel hub and EB weld as an alternative to relying on dowel pins to prevent radial movement of the rim gear.

Fig 2. Gear assemblies welded in a finish machined condition. Materials: SAE 8620 and EN 36 case hardening steels.



Sometimes a component may have to operate in an environment in which, ideally, dissimilar material specifications would be employed, eg, the shaft of a marine pump. Here, a case hardened spur gear (operating in the gear box) could be attached by EBW to a corrosion resistant stainless steel shaft working in the sea water – a case of 'putting the right material in the right place'.

☐ *Component standardisation.* The process can be used to good effect in reducing the number of parts required to produce a range of components, typically where a particular component, such as a shaft, is common to a number of different gears. A very cost effective method for manufacturing ball nuts is shown in fig 3. In this case the aim is to offer a standard range of nuts but with custom-made flanges, often ordered in relatively small batch quantities. In order to respond quickly to customer demand, a minimum stock level of nuts is held, together with the flame-cut blanks for the flanges, but these are only machined and EB welded to their respective nuts on receipt of an order. With an automated machining system completing the flanges and a fast turnaround time for the EBW operation, the response time from ordering to delivery is only a few days.

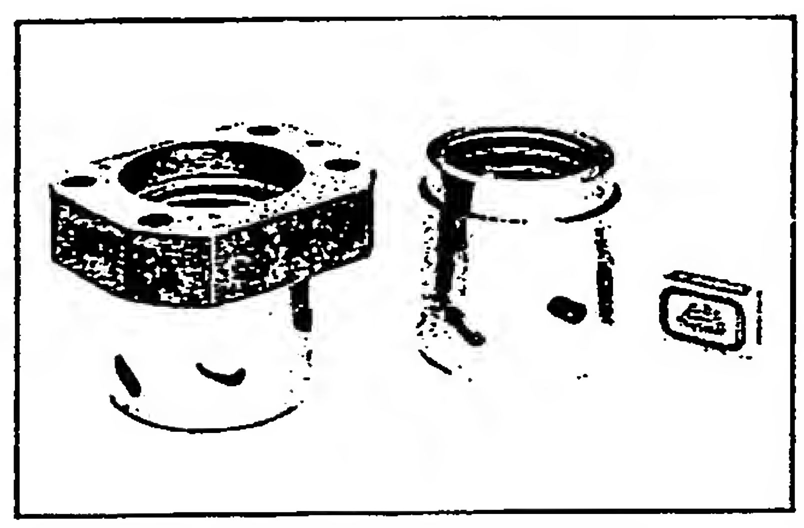


Fig 3. Ball nut with customised flange.

The EB welding process

EBW is a fusion welding process in which the metal is bombarded by a concentrated beam of electrons travelling at a velocity of up to half the speed of light. The kinetic energy of the electrons is converted into heat which is focussed onto a spot under 1mm in diameter, creating an energy density many times greater than that possible in an arc welding operation.

Production welding machines typically operate at powers in the range from 2.5 – 25kW, and joint sections up to about 30mm (1.25in) can be made in a single pass on materials such as steel, nickel and copper alloys, and aluminium alloys. A high voltage electron beam weld is characterised by its extremely high

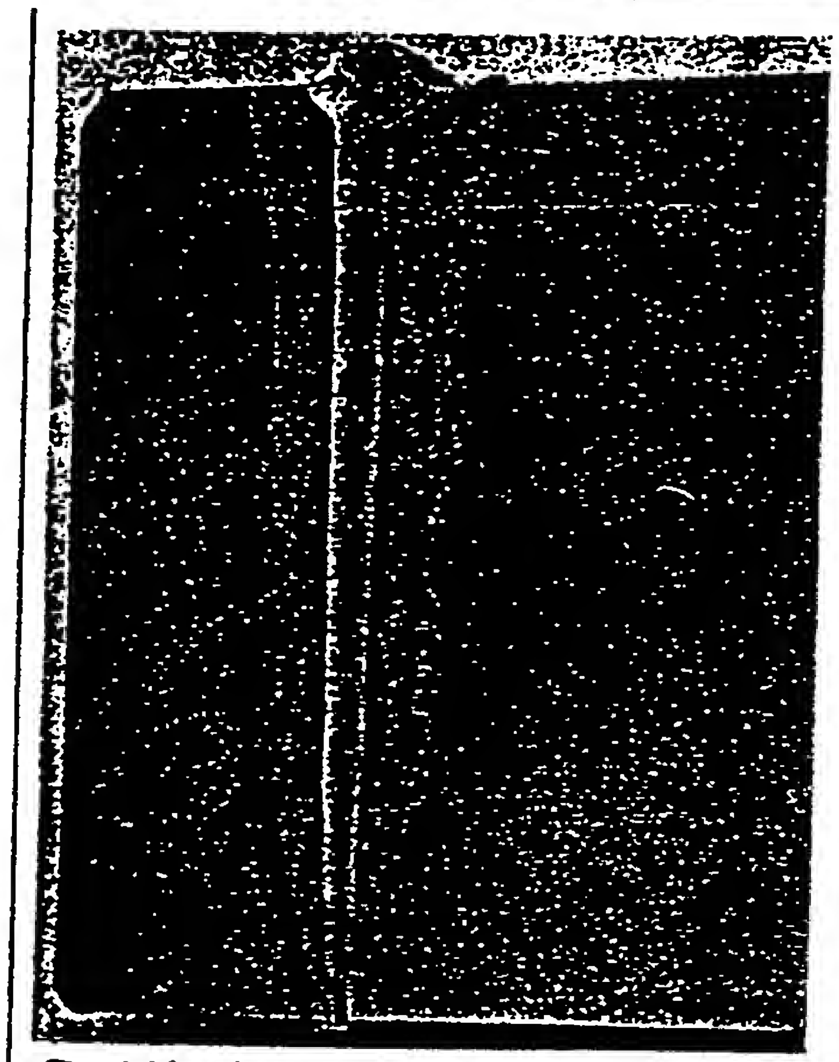


Fig 4. The deep penetration/narrow width ratio characteristic of an EB weld.

penetration-to-width ratio, normally in the order of 20:1, as can be seen in fig 4.

Electrons can be made to travel freely in vacuum (distances over a metre from the emitting gun to the workpiece on larger machines) but are dispersed by collision with gas molecules at atmospheric or even reduced pressures. Therefore EB welding machines normally work at vacuum pressures ranging from $5 \times 10^{-2} - 10^{-4}$ mbar, the work chambers being evacuated by multi-stage pumping systems designed to allow fairly fast evacuation cycles to be achieved even on the larger chambers. (Typically, a pump-down time of under 10 minutes for the production machine shown in fig 5).

Operating in vacuum results in the welding being carried out in a perfect metallurgical environment, ie, without any undesirable oxidation effects. This is a particularly important consideration when processing finish machined components such as gears.

Figure 6 shows schematically how an EB welder operates with the beam in a fixed position and the workpiece manipulated with either a rotary or linear (X-Y) motion in much the same way as in turning or milling.

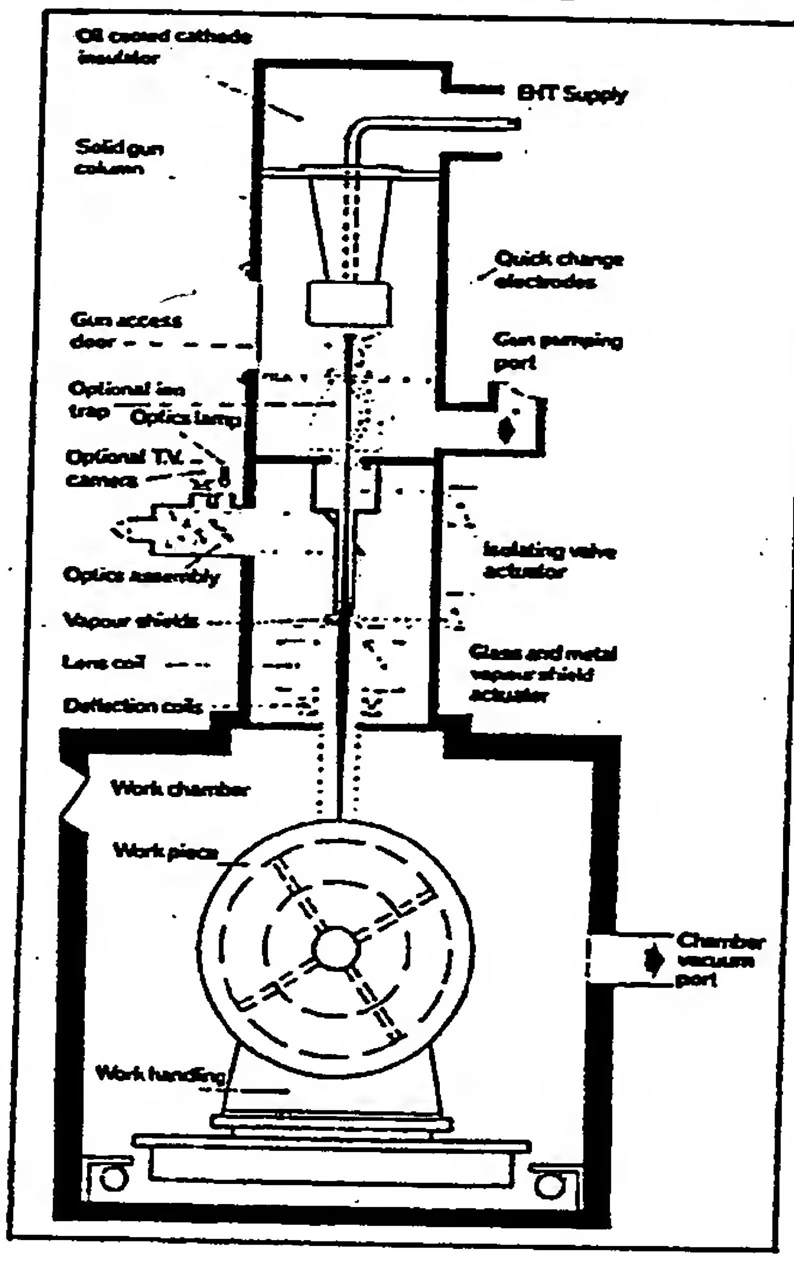
Suitability of gear steels for EBW

EBW is an autogenous welding process, ie, the component parts are joined by fusion without the addition of filler material. As a result of the high energy density levels referred to earlier, welding is carried out at speeds in the region of 12.7 – 25.4mm/sec, (30 – 60in/min). At a given moment in time, the beam creates a molten pool penetrating into the joint section, but as the workpiece is traversed under the beam the original molten spot rapidly freezes behind it. At a welding speed of 60in/min, for example, the beam has effectively moved 1 inch in 1 second, allowing the surrounding mass of metal to quench the weld area quickly by heat conduction.

This heat transfer mechanism is very similar to that occurring during a normal hardening operation, ie, a heating cycle followed by a rapid quench. The resulting metallurgical effect is to increase the hardness of the weld fusion and heat affected zones. Providing that the material being welded does not harden to the stage where stress cracking occurs before it can be tempered, there is no problem. Direct hardening steels with carbon contents under about 0.3% are usually weldable. In welding of gear steels however, it is often necessary to weld components already in the fully heat treated condition which would be degraded metallurgically by a further treatment. At first sight the use of direct hardening steels in welded gear fabrications does not seem very attractive but there are a limited number of material grades which are both weldable and also commonly specified for use in gear manufacture.

It is sometimes necessary to compromise, as in the case of welding a nitriding steel such as 722M24 (EN40B). After welding, this material should ideally be tempered at 625°C

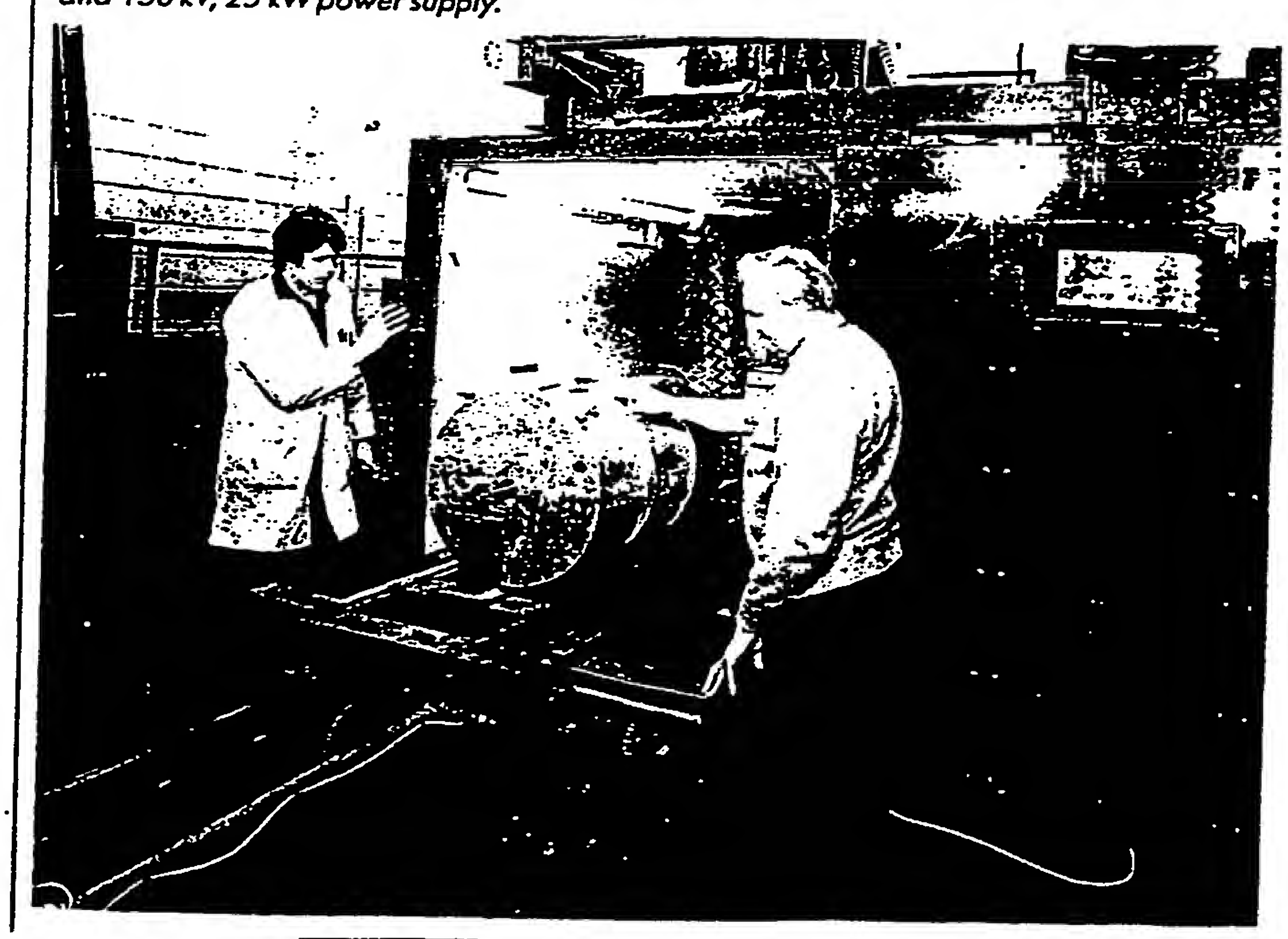
Fig 6. Features of an EB welding machine.



to reduce the hardness in the weld fusion and heat affected zones to near parent metal condition. If the component is to be nitrided after welding, however, this treatment, typically 510°C for 80 hrs, will result in the weld hardness level being substantially reduced and make further treatment unnecessary. In fig 7, hardness values in the weld fusion zone and the parent metal are compared for the 'as welded' and nitrided conditions.

The narrow width of the fusion zone in an EB weld often allows stresses resulting from an increase in hardness to be restrained without cracking occurring. There are limits, however, and in practice it is better to select a grade of material with the lowest carbon content which meets the service requirements of the component. Case hardening steels present no such problems, and practically all the grades normally used for making

Fig 5. HSD Dynaweld model 956 EB welding machine with a 9ft by 5ft by 6ft work chamber and 150 kV, 25 kW power supply.



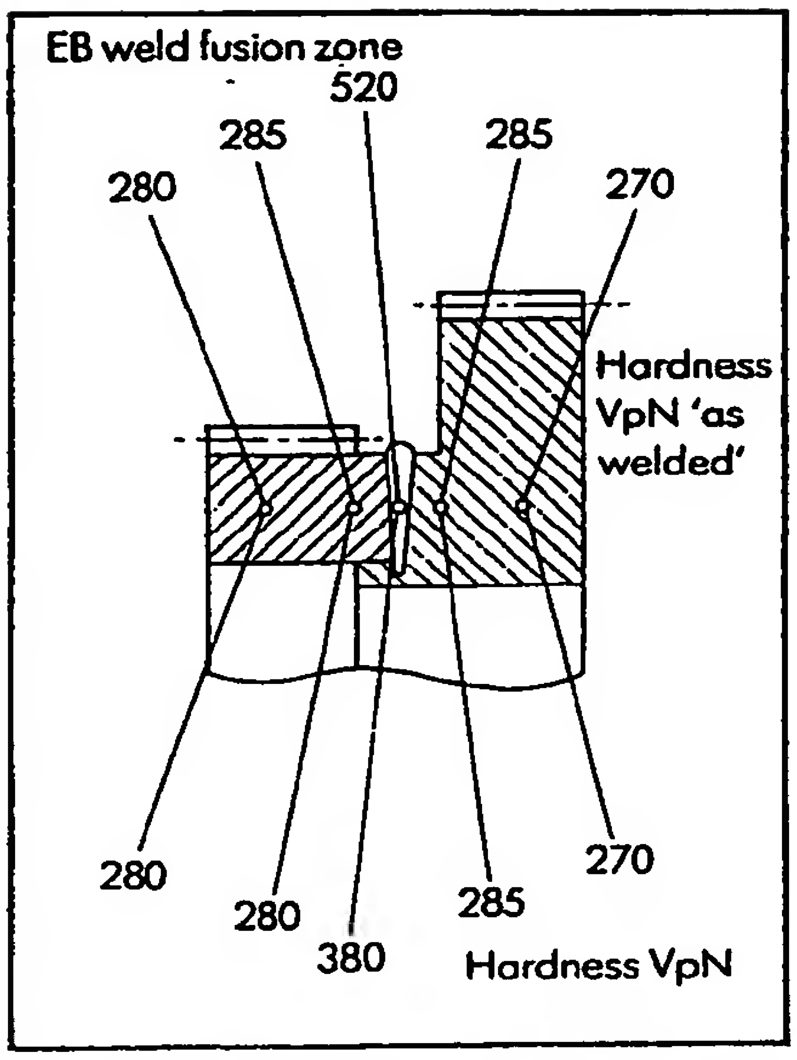


Fig 7. Hardness values in welded gear section before and after nitriding treatment. Material: 722M24 (EN40B). Hardness values – Vickers (VpN), Heat treatment – nitrided at 510°C for 80 hours.

transmission parts are weldable.

In Table 1 a selection of direct and case hardening steel specifications is listed and their weldability indicated. Where a 'poor' rating is given against a particular specification this does not necessarily mean the material is unweldable, but suggests that weld development will certainly be required before proceeding with manufacture. Alternatively, the use of a more weldable grade could be considered.

The alloying constituents of the various material specifications are included simply to highlight the significance of the carbon content in determining the hardenability (and weldability) of a particular alloy. While other elements such as manganese, chromium and molybdenum also contribute to the hardening properties, their individual effect is much less significant than that of the carbon.

Joint preparation

Because a filler material is not used in EB welding under normal circumstances, the familiar 'vee' preparation associated with conventional arc welding practice is not required; the process basically fuses together two metal sections held in close abutment. This makes the machining of component parts very straightforward as there are really only two joint designs used in gear fabrications – plain and spigotted butt preparations.

As it is a precise welding technique, EBW is rather more demanding in terms of the machining standards required in preparing joints than conventional welding. However, because transmission parts are in any case produced to close machining tolerances, these two factors complement one another and the standards of surface finish and dimensional tolerances normally used are quite adequate for EBW.

In fig 8 cut away drawings of some typical components serve to illustrate the simplicity of EB joint configurations commonly used for welding gear clusters, splined shafts, flanged couplings, etc. These examples also serve to emphasise the point made earlier concerning the potential savings to be made in material costs and machining times in producing such parts.

Gap tolerances and fit conditions

As a guideline for circumferential and planetary (axial) joints, gap tolerances on weld abutment faces should normally not exceed 0.05mm (0.002in) on joint sections up to about 16mm (0.625in) thickness and 0.10mm (0.004in) on heavier sections. A gap in this context could result from the abutment faces not being machined square and true and so not closing in absolute contact across the joint faces.

For parts that are to be assembled for a planetary weld an interference fit condition is required in order to counteract the contraction resulting from the welding operation. As a general rule of thumb, an interference of 0.025mm per 25mm diameter is satisfactory for joints up to about 150mm (6in) diameter, but for larger diameters an interference of 0.15mm (0.006in) is usually adequate.

Circumferential joints can be machined with either a plain or spigotted butt preparation depending on design considerations. Plain butt joints require the component parts to be located concentrically on a mandrel which also serves to hold them together under light pressure during the welding operation. Introducing a location spigot can simplify fixturing of the parts if they are machined to be self-locating on assembly so, if a mandrel is used, it acts more as a tie bar, with the spigot providing concentricity alignment.

There are a few simple but important rules to follow when machining spigots and their mating recesses as, not surprisingly, an incorrectly machined joint preparation can adversely affect weld quality. A common error in machining spigot preparations is to chamfer heavily the inside edge of the mating component in order to ensure that the joint faces are in complete abutment when assembled. While the intention is commendable, the effect can be the removal of a substantial part of the joint section which could otherwise have formed part of the weld. As a guide, it is better to instruct the machinist to 'break edge' rather than 'chamfer'.

Where a spigot registers within a recess it is important that the depth of the recess is made slightly longer than

Table 1 Weldability of direct hardening and case hardening steels commonly used in transmission component manufacture

MATERIAL GRADE	SPECIFICATIONS BS	EN	CONSTITUENTS % C	Mn	Cr	Mo	WELDABILITY RATING[1]
C/Mn steels – direct hardening	These grades generally unsuitable for EB welding						
Typical alloy steels direct hardening	817M40	24	0.36/0.44	0.45/0.70	1.00/1.40	0.20/0.35	P
	835M30	30B	0.26/0.34	0.45/0.70	1.10/1.40	0.20/0.35	S
	722M24	40B	0.20/0.28	0.45/0.70	3.00/3.50	0.45/0.65	S
	897M39	40C	0.35/0.43	0.45/0.70	3.00/3.50	0.80/1.10	P
Typical case hardening steels	637M17	352	0.14/0.20	0.60/0.90	0.60/1.00	—	S
	815M17	353	0.14/0.20	0.60/0.90	0.80/1.20	0.10/0.20	S
	—	36B	0.12/0.18	0.30/0.60	0.60/1.10	—	S
	822M13	36C	0.10/0.16	0.35/0.60	0.70/1.00	0.10/0.25	S
	835M15	39B	0.12/0.18	0.25/0.50	1.00/1.40	0.15/0.30	S

[1]Weldability ratings – S = satisfactory, P = poor.

The above grades are typical of those used for gear manufacture. For brevity only elements having a significant influence on the hardening properties are listed. A complete range of material specifications and their composition can be found in Iron & Steel Specifications, BS970 Pt 1.

the protruding spigot – usually about 0.25mm (0.010in) is an adequate gap – to compensate for the contraction that will occur during welding.

Applications and design opportunities

The concept of welding two or more simple machined shapes to form a complex structure is made feasible by the ability of EBW to join metals with near parent metal strength, minimal distortion and only very localised metallurgical disturbance. Design opportunities are created for making components which are compact, economic in their use of materials and cost effective to produce.

EBW is a machine controlled process in which key parameters, determined at the initial development stage, are recorded and applied throughout the production run for that particular component. The control excercised allows repeat batches of components to be produced to a consistent quality standard regardless of batch size or the time elapsing between batches.

Electron beam welding machines are fairly complex, high-cost capital equipment. Installing a machine 'on line' only becomes economically viable where relatively high volume production quantities are envisaged, allowing the plant to be fully utilised, ideally on a double day shift basis. An efficient operating team and ancillary back-up personnel such as NDT, metallurgical and maintenance support are also essential to the successful performance of the facility.

The alternative option is to subcontract the welding operation to a specialist EBW jobbing shop which can provide production capacity on demand and any other back-up services such as non-destructive testing, eg, x-ray and penetrant crack detection. Opting for this route can bring the advantage of a design consultancy service on EB welding based on experience in applying the process to solve practical metal joining problems in an innovative way.

Electron beam welding is a process which challenges the designer to solve problems in a novel manner. Whether the objective is to reduce size and weight, cut manufacturing costs, or simply to build a component in a different way, having a basic understanding of the process and how to exploit it is an essential first step to making the decision to change to electron beam welding. ■

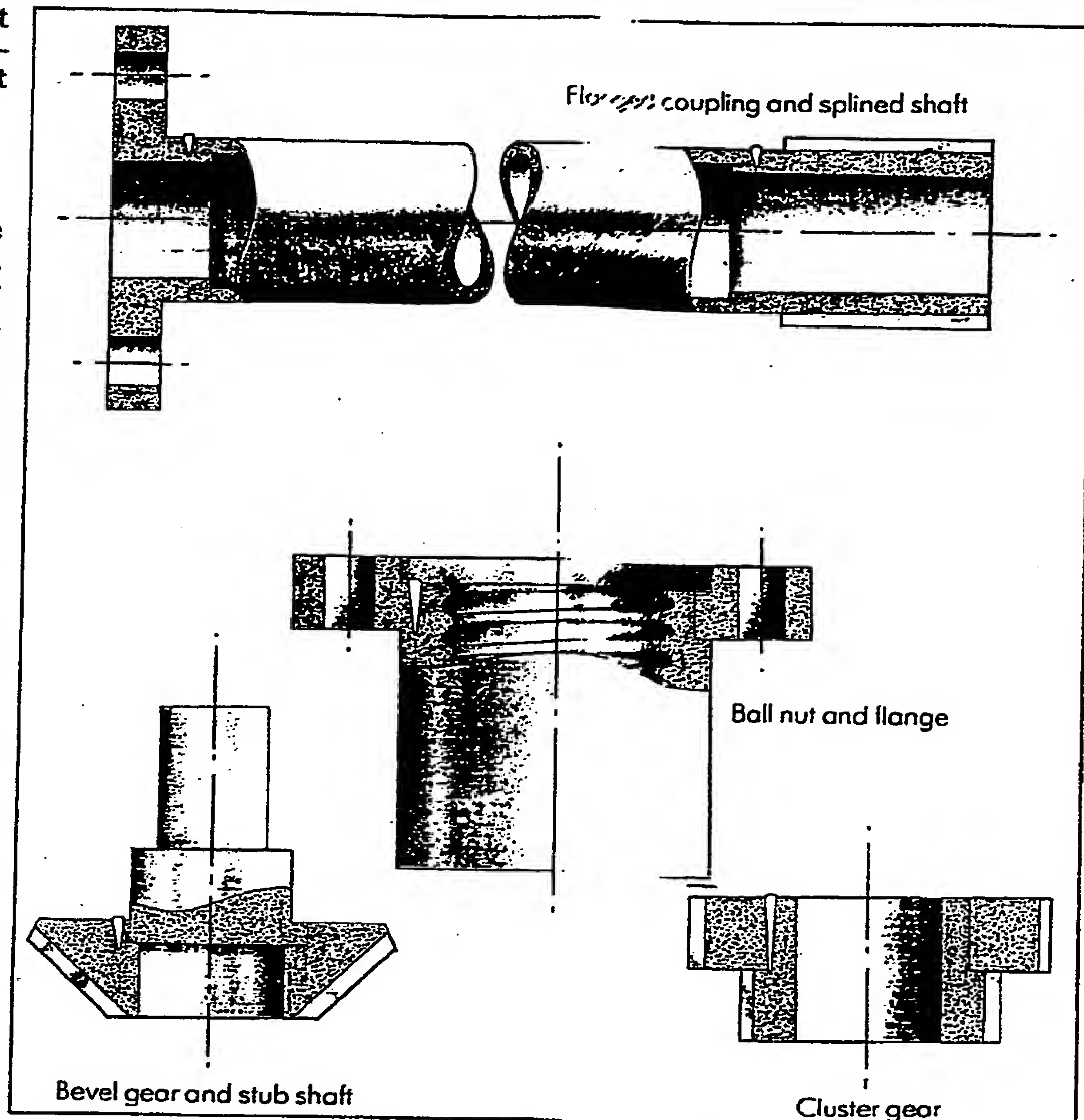


Fig 8. Joint configurations used in fabricating transmission components.

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